The case for a cosmological constant

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Taking the Hubble constant to be in the range 60 - 75 km/s Mpc we show that three independent conditions strongly rule out the standard model of flat space with vanishing cosmological constant.

1 Introduction

The dynamical parameters describing the cosmic expansion are still very inaccurately known, permitting a wide range of cosmological models to appear plausible. Judging from all the information available at present, the Universe is either open, with the total density parameter $\Omega_0 < 1$, or flat by virtual of the presence of a cosmological constant. Let us use the notation

$$\Omega_0 = \Omega_m + \Omega_\lambda = 1 \tag{1}$$

where the density parameter of the vacuum energy is $\Omega_\lambda = \lambda/3H_0^2$, and Ω_m is the density parameter of baryonic + dark matter.

We study here whether the "standard model" of flat space with $\Omega_\lambda = 0$ is still viable in the light of recent determinations of several cosmological parameters.

2 Cosmological conditions

The Hubble constant H_0 used to be uncertain by a factor of two, but it now is converging into the (one standard deviation) range

$$H_0 = 67 \pm 6 \text{ km s}^{-1}\text{Mpc}^{-1}. \tag{2}$$

This value is the result by Nevalainen & Roos (1997) of combining H_0 determinations from four HST-observed galaxies, and applying the correction due to the metallicity dependence

of the Cepheids, as determined by Beaulieu & al. (1997) and Sasselov & al. (1997), to Cepheids in M96 (Tanvir & al. 1995) and M100 (Freedman & al. 1994) and to the supernovæNGC 5253 (Sandage & al. 1994) and IC 4182 (Saha & al. 1994, Sandage & al. 1994). If one takes into account the correction to the Cepheid period-luminosity relation measured by Hipparcos (Feast & Catchpole 1997) the above H_0 value may still go down by 10%, but we feel that it is still not quite settled whether this is justified at the distances in question.

An age limit of the Universe can be taken from the age of the oldest globular clusters. Making use of the new distance measurements by Hipparcos, Chaboyer & al. (1997) estimate their mean age to be

$$t_{globulars} = 11.5 \pm 1.3 \text{ Gyr} \tag{3}$$

To which the unknown age of the Universe at the time of their formation must be added. An even more stringent limit is posed by the discovery (Dunlop & al. 1996, Kashlinsky & Jimenez 1996) of a weak and extremely red radio galaxy 53W091 at $z = 1.55$ whose spectral data indicate that its stellar population is at least 3.0 Gyr old. Although Bruzual & Magris (1997) have claimed that this age determination is an artifact, we shall explore the consequences of such an old object.

In the Friedman-Lemaître model the age $t(z)$ of the Universe at redshift z can be expressed in the form

$$\begin{aligned} t(z) &= \frac{1}{H_0}\int_0^{1/(1+z)} \mathrm{d}x[(1-\Omega_m-\Omega_\lambda) \\ &+ \Omega_m x^{2-3(1+\alpha)} + \Omega_\lambda x^2]^{-1/2}. \end{aligned} \tag{4}$$

Here α is the ratio of pressure to energy density, thus it defines the equation of state. For ordinary or dark non-relativistic pressureless matter $\alpha = 0$. For a flat, static Universe with a cosmological constant $\alpha = -1$.

Using the Dunlop & al. (1996) age of the radio galaxy 53W091,

$$t(z) = t(1.55) = 3.5 \text{ Gyr} \tag{5}$$

Eq.(4) constrains the space of H_0, Ω_m, Ω_λ and α. In figure 1 we plot the solution to Eq.(4) for $\alpha = 0$ and the limit (4) for several values of H_0. It is obvious that the standard corner $(\Omega_\lambda = 0, \Omega_m = 1)$ is then strongly disfavoured by the H_0 value (2).

The only way to reduce the age below 3.0 Gyr is to reduce the product $\Omega_m H_0$, but this then reduces the small scale power in the primordial density field beyond allowed limits.

One degree of freedom which can be used to improve this situation has been pointed out by Steinhardt (1996). Although α is traditionally taken to be zero, in a universe with interacting fields and topological defects α can vary between -1 and 0. This implies the presence of strings causing more small scale power than in simple inflation. In Figure 2 we plot the situation with $\alpha = -0.1$ for different H_0-values. This moves the allowed region towards the standard corner. However, the price paid for this improvement may seem too high, also in view of the next conditions below.

Let us alternatively look at the consequences of taking t_0 to be given by the age of the globular clusters. The Chaboyer & al. (1997) determination carries a 1σ error of 1.3 Gyr. Let us assume that the age of the Universe at the time of their formation is short enough to be included in this error, then we may take

$$t_0 \approx 11.5 + 1.3 \text{ Gyr} = 12.8 \text{ Gyr}. \tag{6}$$

Requiring Eq.(4) to yield this value when H_0 has the value in Eq.(2), one finds that

$$\Omega_m = 0.40 \,^{+0.15}_{-0.10} \tag{7}$$

in a flat Universe. Thus a considerable Ω_λ-component is required. In an open Universe with $\Omega_\lambda = 0$, Ω_m would be very small, 0.3 at most.

The second condition ruling out the standard model is the observational value of Ω_m as determined by X-ray studies of gas in clusters, e.g. the Coma cluster (White & al. 1993) and the rich cluster A85 (David & al. 1995, Nevalainen & al. 1997). Assuming that the gravitating matter seen in these galaxies out to a radius of about 3 Mpc extrapolate well to the average matter density of the Universe, one can obtain a value for the quantity $(\Omega_B/\Omega_m)h^{3/2}$. To evaluate Ω_m one needs to know the baryonic density parameter Ω_B which is highly controversial, due to the conflicting deuterium observations (Rugers & Hogan 1996, Tytler & al. 1996, 1997, Webb & al. 1997). Pushing the gas density profile parameters to their 90% confidence limit, and the Hubble parameter at its lower (two-sided) 3σ limit, $H_0 \geq 50$ km s^{-1}Mpc^{-1}, and taking the D/H ratio to be maximal (Webb & al. 1997), on obtains

$$\Omega_m \leq 0.22\ . \tag{8}$$

Large-scale structures (galaxy correlation functions, the abundance of rich clusters, cluster-cluster correlations etc.) do not constrain Ω_m very tightly, but in the H_0 range (2) they prefer values larger than Eq.(8), $\Omega_m \geq 0.3$ or so. Thus there is some conflict

but in no way driving the solution into the standard corner. Perhaps the solution to this conflict is anti-biasing, or perhaps the X-ray studies of gas in clusters reflect local conditions which are different from cosmological values.

Plotting the limit (8) in Figures 1 and 2 it is obvious that it strongly rules out the standard corner, but it can be made to agree with a flat $\Omega_0 = 1$ universe if the vacuum energy density contribution is large.

The third condition ruling out the standard model is due to strong and weak gravitational lensing. From observations of the clusters Cl $0024 + 1654$ and A370, Mellier & al.(1997) conclude that

$$\Omega_\lambda \geq 0.6. \tag{9}$$

Note that previous lensing studies only gave upper limits, *e.g.* Kochanek (1996) found

$$\Omega_\lambda \leq 0.66 \tag{10}$$

for a flat Universe.

As can be seen in the Figures, these limits are in agreement with the limit (9) and the H_0 range (2) when taking the age of the Universe from the 53W091. It also agrees roughly with the upper limit to Ω_λ from the observations of Perlmutter & al (1997) of the light-curves of seven high redshift supernovæ. When t_0 is taken from the globular clusters, these conclusions are somewhat softened, but qualitatively the same.

We have not made any use of CMB data, because the height of the Doppler peak has not been measured well enough yet to yield information of precision comparable to what was used here. Note that both large-scale structures and the CMB Doppler peak depend on further adjustable parameters which we have not referred to, such as bias b and the spectral index n.

3 Conclusion

Thus our conclusion is that the standard model with $\Omega_\lambda = 0$, $\Omega_m = 1$ is ruled out, some low-density open models are possible, but the preferred range is around $\Omega_\lambda = 0.6 - 0.8$, $\Omega_m = 0.2 - 0.4$, $H_0 = 60 - 75$ km s^{-1}Mpc^{-1} and the flat geometry of Eq.(1) is possible.

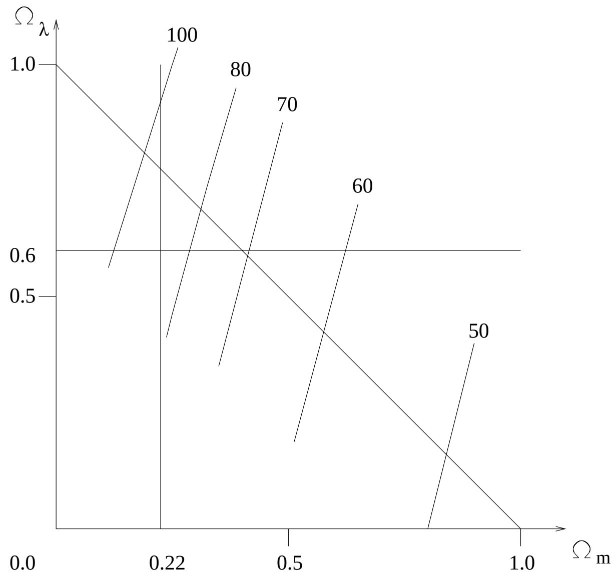

Figure 1: Regions allowed in the $(\Omega_0, \Omega_\lambda)$-space. The set of solid lines are imposed by the observation of the radio galaxy 53W091 assuming $\alpha = 0$. The numbers indicate the value of the Hubble constant in units of km s^{-1} Mpc^{-1}. The limits $\Omega_m < 0.22$, $\Omega_\lambda > 0.6$ are indicated.

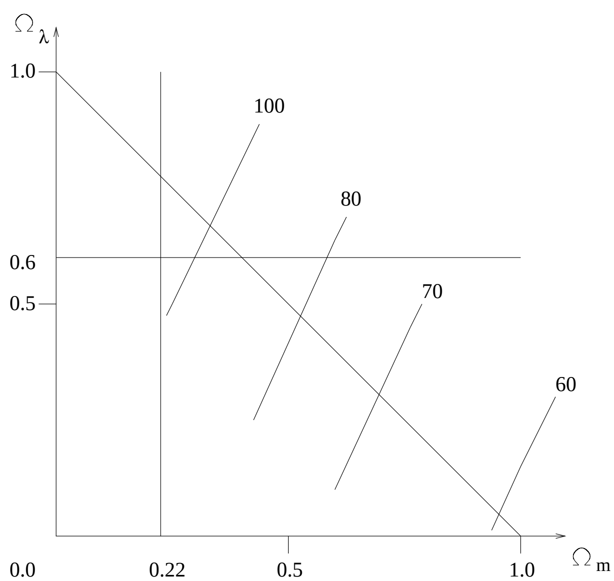

Figure 2: As Fig. 1, but for α = -0.1

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